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Investigating the Feasibility to Remove Alpha Case from Titanium Alloys with Machining

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Abstract
Titanium as an alloy offers excellent material properties including corrosion resistance, biocompatibility and high specific strength. These properties make titanium alloys highly desirable in demanding applications and specialised industries such as aerospace and orthopaedic prosthesis. However, the formation of a hard and brittle alpha case layer at elevated temperatures requires hot forming processes to be conducted either in inert atmosphere, or vacuum. Alternatively, alpha case could be removed post process by chemical milling which requires high capital costs as well as stringent safety measures. Alternative removal techniques are therefore under investigation and one such option is machining removal which can make use of the already established South African machining industry. Excessive wear due to the hardened alpha case layer results in machining removal not currently being viewed as economically feasible. This investigation therefore focusses on identifying possible machining guidelines for the removal of alpha case from titanium alloys. Thereafter, a comparison is made between machining removal of alpha case with chemical milling in the context of the South African manufacturing industry. It was observed that alpha case is readily removed at all machining conditions and that excessive notching and accelerated wear rates are experienced at high cutting speeds. Wear rates more commonly attributed with titanium machining is observed at lower cutting speeds.

Keywords
Alpha case removal, Machining, Titanium

1 INTRODUCTION

At temperatures above 600°C, titanium experiences oxidation through interstitial diffusion where oxygen diffuses into the material substrate. This oxidation results in the formation of a thin, hard and brittle, oxygen enriched surface structure, of mainly alpha phase titanium. Oxidation changes the surface structure and composition, which strengthens and hardens the alloy [1]. Figure 1 illustrates the effect of heat treatment in ambient air on the hardness profile of titanium samples, and shows a two fold increase in hardness close to the edge.

The alpha case layer exhibits an increased Young's modulus (measure of stiffness) compared to the substrate, and the variation in stiffness across the surface of the material causes localised micro failures to form. Fatigue crack initiation areas form as part of the micro failures, compromising the integrity of the component, causing it to fail [3]. Alpha case also causes a significant loss of tensile strength and a reduction in fatigue performance [4]. It furthermore lowers the already low machinability of titanium alloys due to the increased hardness of the surface layer, which is why many titanium hot processes such as welding and melting are performed in vacuum or inert atmosphere [3]. Certain processes such as hot rolling can however not practically be performed in vacuum or inert atmosphere, and alpha case therefore has to be removed post process [5].

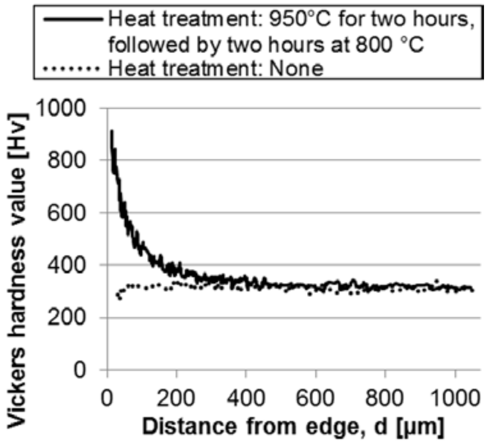

Figure 1 - Hardness depth profile comparison of heat treated and untreated titanium – adapted [2]

Current removal techniques most commonly comprise chemical milling in which the component is submerged into a heated acidic solution whereby aggressive acids etch away the surrounding alpha case. The chemical milling process is not complex but if not properly and safely executed can become hazardous, costly and wasteful in terms of workpiece material, and solution [6]. No chemical milling facilities capable of alpha case removal is currently available in South Africa, and the construction thereof would incur high start-up cost, stringent safety requirements, and extensive reprocessing and disposal cost of used acids. Alternative removal methods are therefore under investigation and one such method is machining removal.

This study aims to determine the possibility of using face milling with indexable tungsten carbide cutting tools as an alternative removal method of alpha case formed during hot rolling, in the context of the South African manufacturing industry. Additional advantages include that further semi finishing and finishing of components can be performed immediately after the removal of the surface layer, and that the safety risks associated with chemical milling will be mitigated. An economic study will also determine if the machining feasibility can translate into economic feasibility.

2 EXPERIMENTAL SETUP AND DESIGN

A wrought, grade five alpha beta alloy Ti6Al4V was be used for this investigation. A purely thermal heat treatment regime, illustrated in Figure 2, was implemented for the formation of alpha case which simulated similar conditions experienced during titanium hot rolling.

The cutting tool used in this investigation was a multifunctional face milling cutter incorporating double negative octagonal inserts. The tungsten carbide cobalt micro-grain cemented carbide cutting inserts are coated with a TiN and TiAlN multi-coat which is applied by physical vapour deposition.

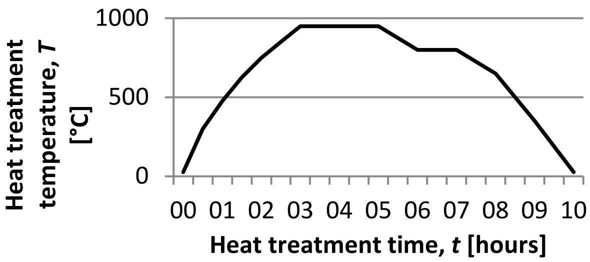

Figure 2 - Heat treatment cycle of titanium samples used for machining experiments

The effect of alpha case on the life of unused carbide cutting tools was investigated at various cutting parameters on a Hermle C40 U Dynamic 5-axis CNC milling machine. The recommended cutting parameters follow the accepted practice for titanium machining of using low cutting speeds in order to promote long tool life. Based on manufacturer recommendations, cutting speed (v_c) was varied between 40, 60 and 80 m/min and cutting feed (f_z) was varied between 0.1, 0.15 and 0.2 mm/z. Depth of cut (a_p) was constant at 1 mm for all machining trials. Down (climb) milling was utilised, causing chips to be formed from thick to thin. Straight line cuts were performed with a width of cut (a_e = 35 mm) equal to 70% of the cutter diameter (50 mm) and the length of cut (255 mm). The cutting speed, feed and cutter depths are listed in Table 1 below.

ISCAR SOF 45				
a_p [mm]	a_e [mm]	z *[inserts]*	f_z [mm/z]	v_c [m/min]
1	35	6	0.1	40
			0.1	60
			0.1	80
			0.15	40
			0.15	60
			0.15	80
			0.2	40
			0.2	60
			0.2	80

Table 1 - Cutting feed and speed combinations for machining experiments

For a satisfactory amount of data to be acquired, samples were machined and heat treated a number of times. Every single machining straight line cut at a specific combination of cutting speed and feed removed roughly 9 cm^2 of material. A total of 100 cm^3 of material were removed before experimentation was halted, unless tool failure criteria were met. Tool wear were measured and quantified via optical microscopy to determine tool failure after every single straight line cut and surface hardness measurements of the workpiece surface were taken to determine if all of the hardened alpha case is removed. Tool life failure is stipulated as average wear on the flank face of all six inserts equalling 350 μm.

3 RESULTS AND DISCUSSION

3.1 Confirmation of successful alpha case removal

Initial heat treatment results in the titanium sample to exhibit a darker red/brown colouration instead of the traditional titanium metallic grey. Flaking is also evident on the outermost surface which is due to the formation of TiO_2 and Al_2O_3 surface layers. This phenomenon is fully described by Du, Datta, Lewis and Burnell-Gray. After machining, the oxidised surface resulting from heat treatment is replaced with the more commonly found metallic colour with traditional wear marks. The newly machined surface is smooth due to the flat rake surface of the carbide insert, with surface roughness ranging from R_a = 0.3 – 1.2 μm, depending on the orientation of the measurement and the cutting conditions.

Apart from surface roughness measurements on the workpiece surface, additional surface hardness measurements were also recorded. This was performed on every machined surface before subsequent heat treatment to confirm the absence of alpha case from the titanium samples. The typical hardness of the specific titanium alloy (Ti6Al4V) used in this investigation is 349 HV. Control hardness measurements of the clean titanium sample before heat treatment and experimentation exhibited a surface hardness of 357 HV.

The surface hardness of newly machined surfaces in which alpha case was removed exhibit average hardness measurements of 336 HV. The average surface hardness values are close to the prescribed titanium surface hardness which indicates that the alpha case layer has been successfully removed for all machining conditions. The feasibility of using machining removal of alpha case from titanium alloys has therefore been confirmed, as the hardened alpha case layer is replaced with the softer titanium substrate. Although this is not a conclusive method for determining alpha case removal, it is satisfactory for most processes. Alpha case machining removal is only a pre-machining operation. Further roughing and finishing operations are still to take place in subsequent operations. Furthermore, the surface integrity of the newly machined surface is also irrelevant as additional machining processes are to be executed on the newly generated surface.

3.2 Tool life

The tool life data and the material removal recorded at various cutting conditions when performing alpha case machining removal from titanium alloy Ti6Al4V are given in Figure 3 below.

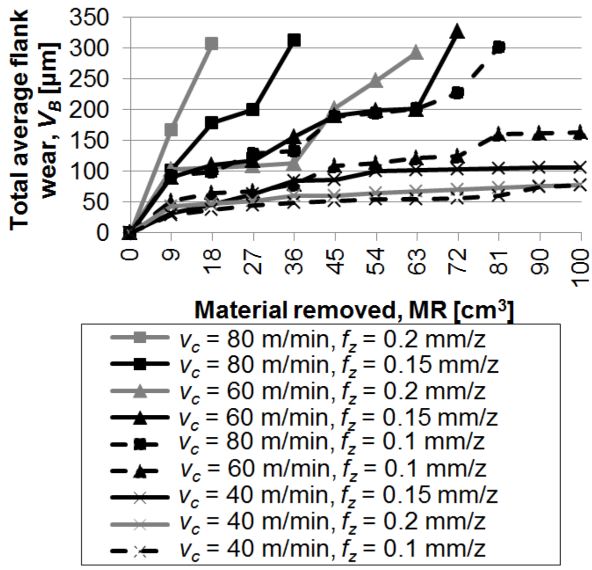

Figure 3 - Wear curves for different feed and speed combinations

As is common with titanium machining and machining in general, is that both the cutting speed and feed rate greatly influences the resulting tool life. The effect of feed rate is however dependent on the cutting speed. Lowering the feed rate from f_z = 0.2 mm/z to f_z = 0.1 mm/z at the highest cutting speed of v_c = 80 m/min, results in a 300% increase in total material removed by the carbide insert. Similar increase is experienced at cutting speed of v_c = 60 m/min, whereby a 200% increase in total material removal is experienced with a reduction in feed rate. However, at the lowest cutting speed of v_c = 40 m/min the effect of feed rate on the carbide wear is negligible as the total amount of material removed is identical for all three feed rates. Of the three different feed rates at cutting speed v_c = 40 m/min, only one (f_z = 0.15 mm/z) experiences slightly higher amounts of wear due to a large chip that formed during the machining trials. Disregarding the effect of the chip on the average tool wear of the remaining carbide inserts result in almost identical levels of wear across all three feed rates.

Different types of wear were recorded for different cutting parameters. At higher cutting speeds, the majority of the wear is restricted to the notch region. This is a special type of wear on the flank face that develops on the same height as the workpiece surface. In this case, it is the same region that contains the hardened alpha case layer. The alpha case layer is therefore directly responsible for the notching and the increased wear experienced by the carbide inert. Also common with this type of wear is that little or no wear is experienced below the notched region. This is illustrated in Figure 4.

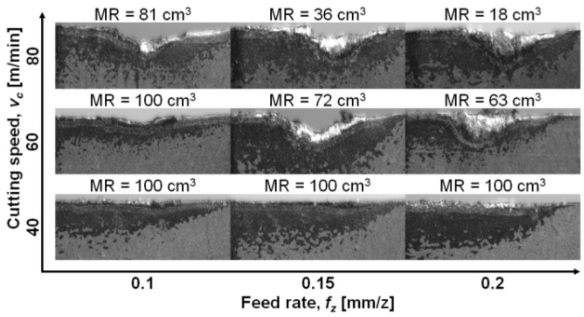

Figure 4 - Final tool wear observed on various cutting edges with the correlating cutting speed vc, cutting feed fz and total material removed MR

At lower cutting speeds, and lower material removal rates, the effect of the hardened alpha case layer is less prominent, and the notching effect experienced at higher cutting speeds is reduced. Gradual flank wear along the length of the cutting edge is experienced on most of the edges at low cutting speeds.

Maximum material removal was fixed to 100 cm^3, and four out of the nine possible machining conditions removed the prescribed amount before tool failure. The tool life for these cutting conditions is therefore not fully established. Furthermore, due to the large increase in wear experienced by some of the cutting tools when close to tool failure criteria, it was decided to declare a tool change slightly earlier than the prescribed amount (300 μm on the flank face). As a result, tool life is extrapolated to estimate total tool life for a total tool wear of 350 μm on the flank face. Linear extrapolation of the data yields total tool life and material removal exhibited in Figure 5.

The line graph represents the total cutting time, and the column bar represents the total amount of material removed. In terms of total cutting time, the more aggressive feed rates (f_z = 0.15 mm/z and f_z = 0.2 mm/z) result in very similar cutting times across all cutting speed ranges. Due to the excessive chipping experienced at the lowest cutting speed v_c = 40 m/min and f_z = 0.15 mm/z, total cutting time and total material removed is reduced. Disregarding the chipped insert from the average tool wear lowers the average tool wear which will consequently increase tool life. Furthermore the total amount of material removed for the particular cutting condition will more closely resemble the results of the other cutting conditions at v_c = 40 m/min.

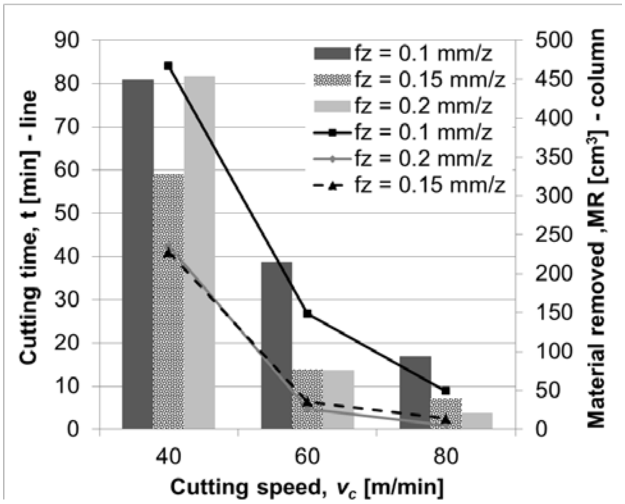

Figure 5 - Tool life projection curve based on extrapolated data observed in experiments

The column bars in Figure 5 illustrates the total material removed for all machining conditions and the shape of the column bars (total material removal) resembles the shape of the line curve (cutting time). At the lowest cutting speed (v_c = 40 m/min) two cutting conditions result in similarly high total material removal however at vastly different total cutting times. The higher material removal rate exhibited by utilising a higher feed rate of f_z = 0.2 mm/z, results in shorter cutting time for similar amount of material removal. This therefore increases the efficiency by removing similar amounts of material in a shorter amount of time. A more detailed analysis will however be required in order to determine the most efficient cutting condition.

Table 2 below illustrates the machining parameters that result in similar material removal rates across various cutting speeds and feeds. As this is a comparison of material removal rates, superior total material removal directly results in more cost effective machining. The least effective combination of speed and feed is at v_c = 60 m/min and f_z = 0.15 mm/z. Utilising a combination of elevated speed and elevated feed is therefore more damaging to tool life compared to high cutting speed and low cutting feed. However, utilising low cutting speed in combination with high cutting feed results in the most economical machining compared to the alternatives.

Feed rate, f_z [mm/z]	Cutting speed, v_c [m/min]	Material removal rate, MRR [cm^3/min]	Total tool life, t [min]	Total material removed, MR [cm^3]
0.1	**80**	10.70	8.8	93.7
0.15	**60**	12.03	6.4	77.0
0.2	**40**	10.70	42.4	453.7

Table 2 - Material removed for each machining speed and feed combination

4 COST MODEL

4.1 Milling Economics

Using the tool life data acquired during experimentation, total machine time and tooling cost can be estimated and an abbreviated unit cost curve similar to can be established. This will however only include the two most basic costs which will serve as an illustration for the basic costs of alpha case machining removal. Figure 6 above depicts the minimum unit cost curve for this investigation for each machining speed and feed combination.

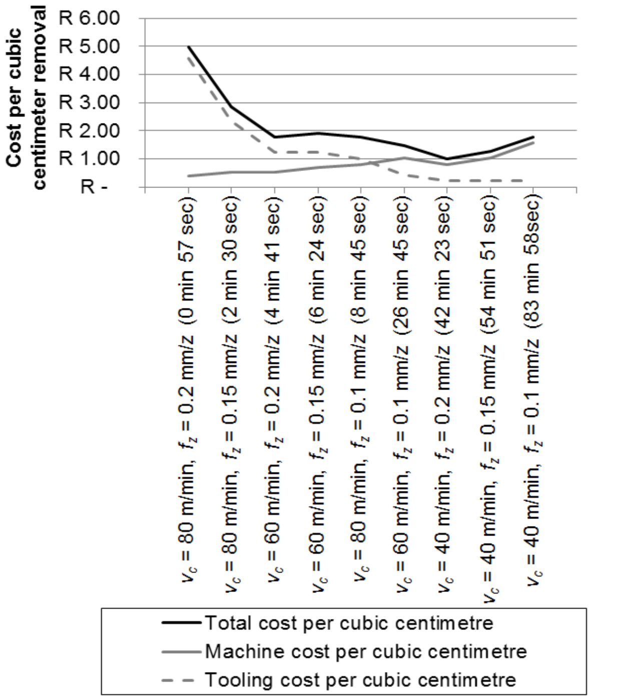

Figure 6 - Minimum cost curve for the removal of one cubic centimetre of material through milling

Cutting time is calculated based on the machining parameters and do not include setup and repositioning or internal tool travel, only actual machining time. The costs involved also only include machine and tooling cost for the removal of one cubic centimetre of material. The sum of the two costs results in the total cost of the removal of one cubic centimetre. The lowest cost of operation can be found at the lowest point in the cost curve. This position is located at a combination of using low cutting speed and high feed rate of v_c = 40 m/min and f_z = 0.2 mm/z.

The resulting unit which is most commonly used in the majority of studies that analyses the economics of milling is cost per cubic centimetre of material removed (ZAR/cm^3). This criterion is also used in this investigation to compare the economics of the different cutting parameters. However, the primary goal is not the removal of maximum volume, but the removal of maximum surface area. In other words, the goal is the clearance of alpha case from the largest possible surface area (cm^2). This investigation used a depth of cut of one millimetre for all machining experiments. This translates one cubic centimetre into ten square centimetres of surface area. Different depths of cut will result in different volumes of material removal; however the surface area will remain similar. As a result, the pre-machining alpha case removal operation can pre-machine titanium blocks closer to specified requirements before actual machining.

4.2 Break Even Analysis

The applicability of machining in the removal of alpha case from titanium comes down to feasibility. Both feasibility of removal, and economic feasibility. Feasibility of machining removal has been proven at low cutting speeds and high feed rates. The final question that needs to be addressed is; can the cost of machining realistically compete with the cost of chemical milling, and under what conditions in the context of the South African manufacturing industry. In order to come to a conclusion, the most economical machining conditions must be established, and the cost thereof should be compared to chemical milling.

In favour of machining removal is that machine shops are readily available in South Africa. With minor advances, titanium machining competency can be established. Supplementary equipment can also be acquired to further expand machining output. Such equipment can additionally be used for further finishing of titanium components, or be used for completely different tasks. The majority of the expenses associated with machining removal will be limited to consumables, labour and machine cost (variable cost). There is no requirement for high capital expenditure and start-up costs for new facilities and equipment (except for the acquisition of additional milling equipment). Furthermore, no training, safety equipment or additional safety requirements are necessary, and machining can start immediately as soon as the need arises using the prescribed guidelines. The costs of machining removal are therefore given in Figure 7 (a).

As there are no chemical milling facilities in South Africa, such facilities must first be constructed. Apart from the acquisition and construction of the facility; the equipment, safety measures and the practical skills required for chemical milling is not available in South Africa, and would need to be sourced from abroad. Additionally, extensive training will be required for new labourers with special emphasis on safety. The requirements listed above must first be obtained at high initial capital investment and will take a long period of time to fully be established. However, in favour of chemical milling is the low variable and maintenance cost. Once the facilities are up and running and a constant flow of projects are secured, chemical milling becomes a more economically viable option. The combination between the required capital investment and its variable cost is depicted in Figure 7 (b).

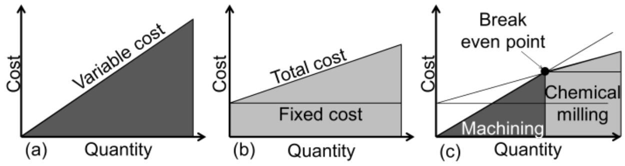

Figure 7 - Cost comparison of (a) machining removal, (b) chemical milling and (c) combined comparison of machining removal and chemical milling for small, medium and large theoretical quantities

Due to the costly nature of the initial capital investment required for chemical milling it is not deemed a viable option for low to medium quantities. Multi-purposing CNC milling machines to alpha case removal as well as final product machining is a more economical option overall. However, increasing the throughput of chemical milling would decrease the fixed cost per part of each individual component. This will ultimately lower the overall cost per part of chemical milling over the long term and increase profitability. In other words, at low- to medium quantities, machining remains the most economical option. However at medium to high quantities chemical milling could become more attractive financially. This break even schematic is shown in Figure 7 (c).

Chemical milling brings with it the use of highly acidic and dangerous acids which inherently increases the risk of using this removal method. Equipment and labourer safety must therefore at all times be the top priority. Acidic solutions must be properly stored in appropriate containers, and used solutions must be processed and disposed of in a manner that will endanger neither the operators nor the environment. Proper procedures should be in place in case of a chemical spill, and medical equipment and trained medical personnel must also be readily available should the need arise. Due to the nature of these risks, an extensive cost benefit analysis should be completed in order to determine if at a specific profitability, the risk of chemical milling not outweighs the benefit of the hazardous operation.

5 CONCLUSION

This paper determined the feasibility of alpha case removal from titanium alloys by method of machining, and the conditions which will allow this removal method to become economically feasible. Alpha case was successfully removed for all machining experiments. It was determined that at high cutting speeds the wear rates of the carbide cutting inserts are high and that unsatisfactory tool life is achieved. At lower cutting speeds however, tool life increased significantly and total material removal is similar to what is expected in traditional titanium machining operations. The removal of alpha case from heat treated titanium is therefore possible through machining, and the recommended machining parameters are high feed rates in combination with low cutting speeds.

Due to the high start-up costs and the stringent safety requirements, chemical milling is not deemed a viable option in South Africa for low production volume as the start-up cost will not be recuperated over the long term. Alpha case machining removal is therefore recommended using already established machine shops for low to medium production volume. Only at high production volumes will chemical milling be able to recuperate the high capital investment over the long term as the variable cost of machining removal becomes too high. The feasibility of machining removal is therefore possible in the South African manufacturing industry with low to medium production volumes.

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8 BIOGRAPHY

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